ADVANCES IN RF CONTROL FOR HIGH GRADIENTS

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Abstract

Superconducting cavities exhibit a high susceptibility to mechanical perturbations due to the narrow bandwidth of the cavities. Significant phase and amplitude errors can be induced by the frequency variations excited by microphonics and Lorentz force detuning. The dynamical Lorentz force detuning of cavities operated in pulsed mode at high gradients (>15 MV/m) can approach the cavity bandwidth thereby demanding substantial additional power for field control. Considerable experience of rf control at high gradients with pulsed rf and pulsed beam has been gained at the TESLA Test Facility in which presently 16 cavities are driven by one klystron. The rf control system employs a completely digital feedback system to provide flexibility in the control algorithms, precise calibration of the vector-sum, and extensive diagnostics and exception handling capabilities. The control algorithm for the vector-sum is based on a proportional controller with timevarying setpoint which is supplemented by an adaptive feedforward to provide further suppression of the dominating repetitive errors caused by beam loading and Lorentz force detuning. The operability of the system is enhanced by automated procedures which assist the operator in the calibration of the vector-sum, measurement of the beam phase, cavity detuning, and other rf system parameters.

1 INTRODUCTION

The superconducting cavities at the TESLA Test Facility (TTF) have been in operation for more than 2 years. While initially one cryomodule with 8 cavities has been operated routinely at gradients up to 15 MV/m, the 16 cavities which are presently installed can be operated at gradients up to 20 MV/m. During beam operation the performance of the rf control system [1] has been studied in detail and improvements in the control algorithms, rf system diagnostics, and automation of various procedures have been made. Significant progress has been possible due to the fully digital implementation of the rf control which allow purely software based modifications of the control algorithms thereby avoiding time consuming changes in the controls hardware. In addition to the fast digital feedback the forward power, reflected power, and the cavity probe signals of each cavity are monitored and the information is used for off-line diagnostics. The rf diagnostics available include the calibration of the vector-sum, calibration of individual cavity gradient and beam phase, measurement and adjustment of the incident wave to each cavity, measurement of the loop phase, and calibration of the loop gain. Application programs are available to monitor the performance of the rf control, activate an adaptive feedforward [2], provide additional rf system parameters through system identification [3], exception handling, and semi-automated turn-on procedures.

2 REQUIREMENTS FOR RF CONTROL

The basic demands on an rf system are stated in terms of required amplitude and phase stability. One constraint to be observed is that the rf power needed for control must be minimized. The rf control system must also be robust against variations of system parameters such as beam loading and klystron gain. Other design issues include reliability and operability. The latter one is substantially enhanced through application programs to support operational aspects such as turn on of the rf system, calibration of gradient and phase, and control of the frequency tuner.

A special requirement imposed on the rf control at the TTF is dictated by the pulsed structure of rf and beam as shown in Figure 1. Although field control appears to be only necessary during the flat-top duration of 800µs where the beam is accelerated, it is desirable to control the field during cavity filling to ensure proper beam injection conditions. Field control is complicated by the transient induced due to the pulsed nature of the beam.

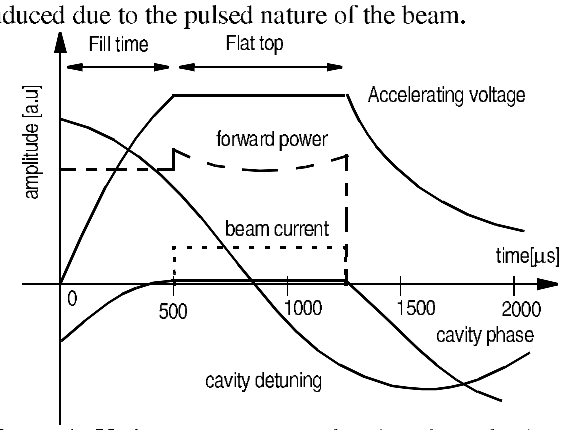

Figure 1: Various parameters related to the pulsed cavity fields in the superconducting cavities of the TESLA Test Facility.

The requirements for amplitude and phase stability of the vector-sum of 32 cavities are driven by the maximum tolerable energy spread for the TESLA Test Facility. The goal is an rms energy spread of $\sigma_E/E = 2 \cdot 10^{-3}$. The requirements for gradient and phase stability are therefore of the order of $2 \cdot 10^{-3}$ and 0.5° respectively.

3 SOURCES OF FIELD PERTURBATIONS

There are two basic mechanisms which influence the magnitude and phase of the accelerating field in a superconducting cavity:

- modulation of the sources of field excitation
- modulation of the cavity resonance frequency

Perturbations of the accelerating field through time varying field excitation are dominated by changes in beam-loading. One must distinguish between transients caused by the pulsed beam and stochastic fluctuations of the bunch charge. The transient caused by the beam pulses in the TTF are of the order of 1%/10µs, while bunch charge fluctuations (uniform frequency spectrum up to 1MHz) of 10% induce field fluctuations of about 1%. In both cases the low pass characteristics (stored energy!) of the cavity have reduced the effect of fast source fluctuations on the cavity field. The excitation of higher order modes also represents a perturbation of the field distribution of the accelerating field.

Mechanical changes of the shape and eigenfrequency of the sc cavities caused by microphonics are a source of amplitude and phase jitter which has bothered sc accelerator technology throughout its development. The sensitivity of the resonance frequency to cavity deformations is of the order of 300 Hz/µm for TESLA cavities. Heavy machinery can transmit vibrations through the ground, support, and the cryostat to the cavity. Vacuum pumps can interact with the cavity through the beam tubes and the compressors and pumps of the refrigerator will generate mechanical vibrations which travel along the pipes and heat exchangers of the refrigerator and the He transfer line into the cryostat until they reach the cavity. Also pressure variations will lead to changes in resonance frequency.

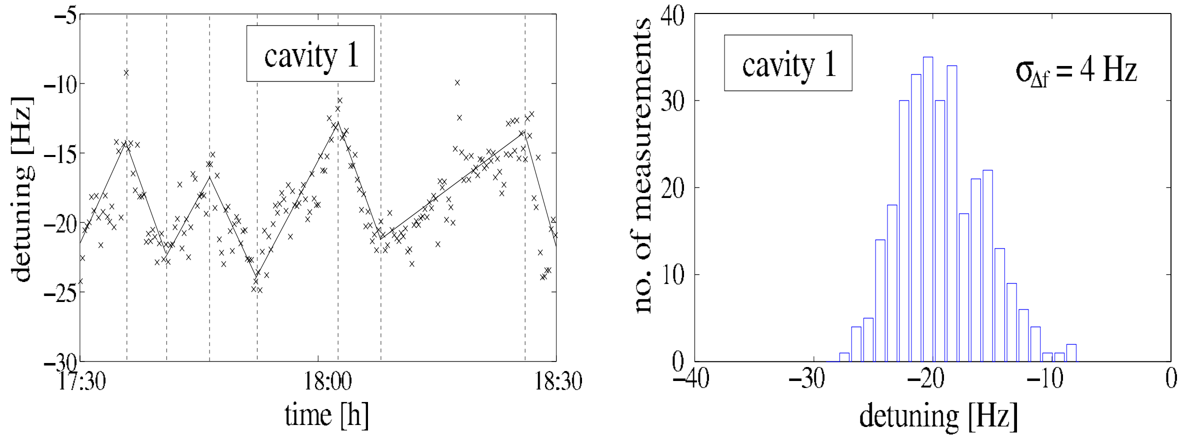

Figure 2: Fluctuations of the cavity resonance frequency. a) Slow drifts over a period of one hour and b) probability density of the cavity resonance frequency with an rms width of 2Hz - 7Hz.

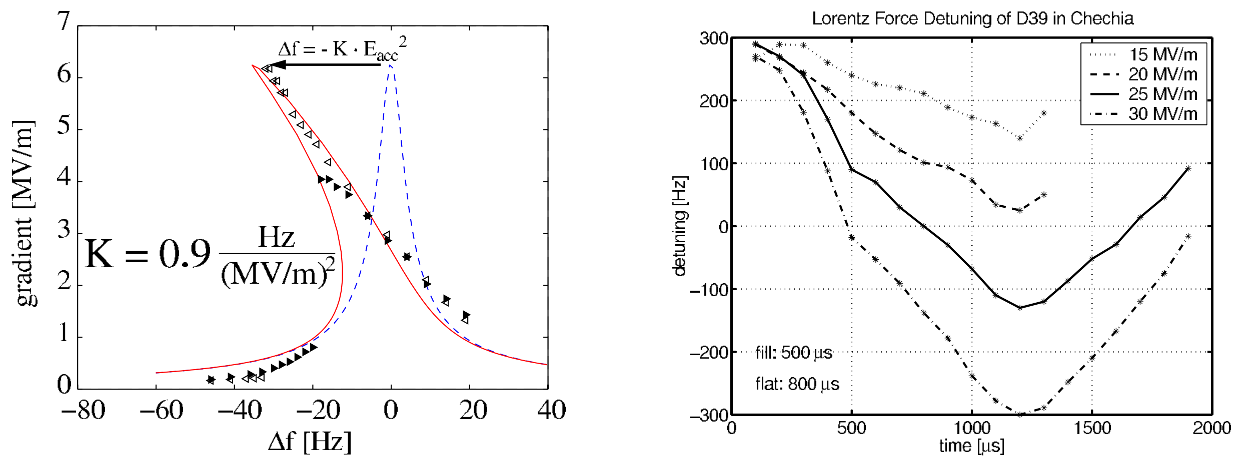

Figure 3: Influence of radiation pressure on the resonance curve of a sc cavity. a) Static detuning during cw operation and b) dynamical detuning during nominal TESLA pulse.

With increasing accelerating gradients the influence of radiation pressure (the interaction of the cavity with its own electromagnetic field) becomes an important effect. The static frequency change is proportional to the square of the accelerating field according to $\Delta f = -K*E_{acc}^2$. The constant K which describes the sensitivity of the cavity resonance to the Lorentz force is a function of cavity shape, wall thickness, yield strength of the material, and the mechanical properties of the cavity fixture inside the cryostat.

4 RF CONTROL DESIGN CONSIDERATIONS

The amplitude and phase errors to be controlled in the TESLA linac are of the order of 5% and 20 degrees respectively as a result of Lorentz force detuning and microphonics. These errors must be suppressed by a factor of at least 10 which implies that the loop gain must be adequate to meet this goal. Fortunately, the dominant source of errors is repetitive (Lorentz force and beam transients) and can be reduced by use of feedforward significantly. It should be noted that bunch-to-bunch fluctuations of the beam current cannot be suppressed by the rf system since the gain bandwidth product is limited to about 1 MHz due to the low-pass characteristics of the cavity (200 Hz), bandwidth limitations of electronics and klystron (1 MHz), and loop delay of about 1 µs.

5 DESIGN OF THE TTF RF SYSTEM

Fast amplitude and phase control can only be accomplished by modulation of the incident wave which is common to the 32 cavities. Therefore fast control of an individual cavity field is not possible. The modulator for the incident wave is designed as an I/Q modulator to control the in-phase (I) and quadrature (Q) component of the cavity field instead of the traditional amplitude and phase modulators. The coupling between the loops is therefore minimized and control in all four quadrants is guaranteed.

The detectors for cavity field, and incident and reflected wave are implemented as digital I/Q detectors. The rf signals are converted to an IF frequency of 250 kHz and sampled at a rate of 1 MHz, i.e., two subsequent data points describe I and Q of the cavity field. The I and Q component which describe the cavity field vector are multiplied by 2x2 rotation matrices to correct the phase offsets and to calibrate the gradients of the individual cavity probe signals. The vector-sum is calculated and a Kalman filter is applied. The Kalman filter provides an optimal state (cavity field) estimate by correcting for delay in the feedback loop and by taking stochastic sensor and process noise into account. Finally the set point is subtracted and a time optimal gain matrix is applied to calculate the new actuator setting (I and Q control inputs to a vector modulator). Feed forward is added from a table in order to minimize the control effort. The feed forward tables are adaptively updated to reflect slowly changing parameters such as average de-tuning angle, microphonic noise level, and phase shift in the feed forward path.

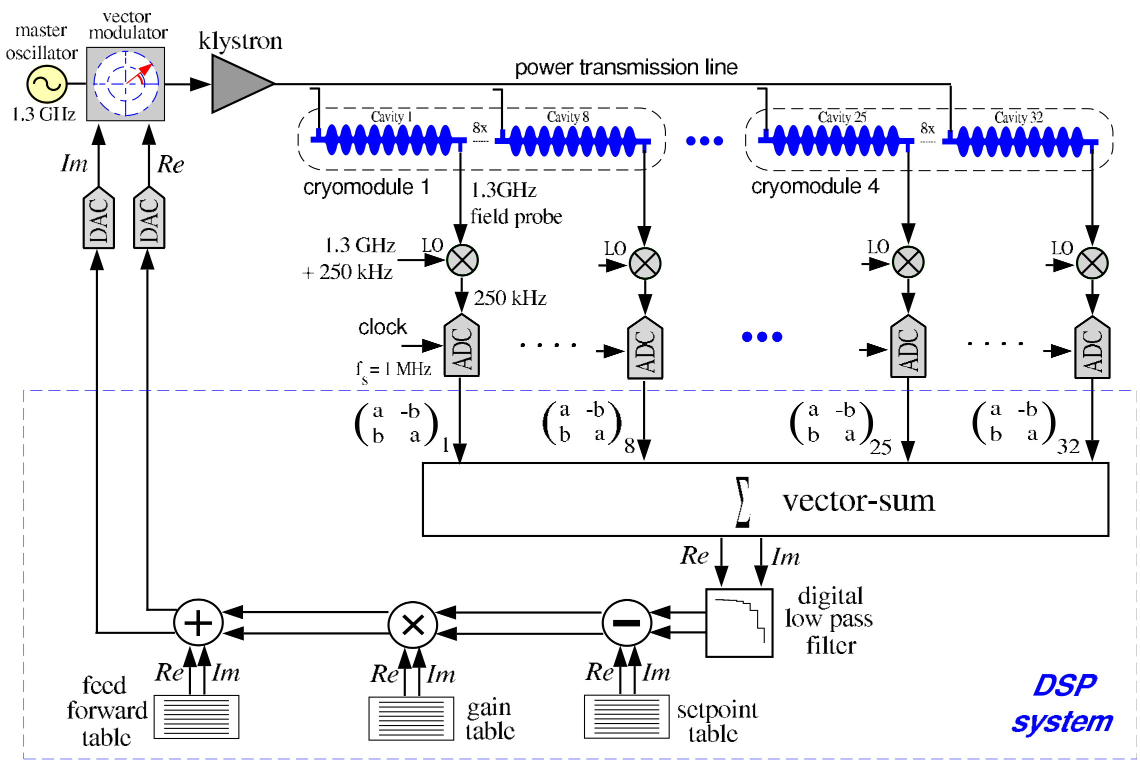

Figure 4: Schematic of the digital rf feedback system.

6 OPERATIONAL EXPERIENCE

The purpose of the TESLA Test Facility is to demonstrate that all major accelerator subsystems meet the technical and operational requirements of the TESLA 500 linear collider. Currently the TTF linac is operational with 16 cavities installed in two cryomodules. Despite the fact that the second bunch compressor is installed between the two cryomodules all 16 cavities are driven by a single klystron. In TTF mode the bunch compressor is by-passed by a straight section and the vector-sum of 16 cavities is controlled. During FEL operation only the vector-sum of the first 8 cavities is regulated in order to maintain stable injection conditions into the bunch compressor. The cavities are routinely operated at 15 MV/m which is the design gradient for the TTF providing a beam energy of 260 MeV. Based on the result of vertical tests, module 1 is expected to operate above 20 MV/m while module 2 has demonstrated 18 MV/m limited by one of the rf power couplers.

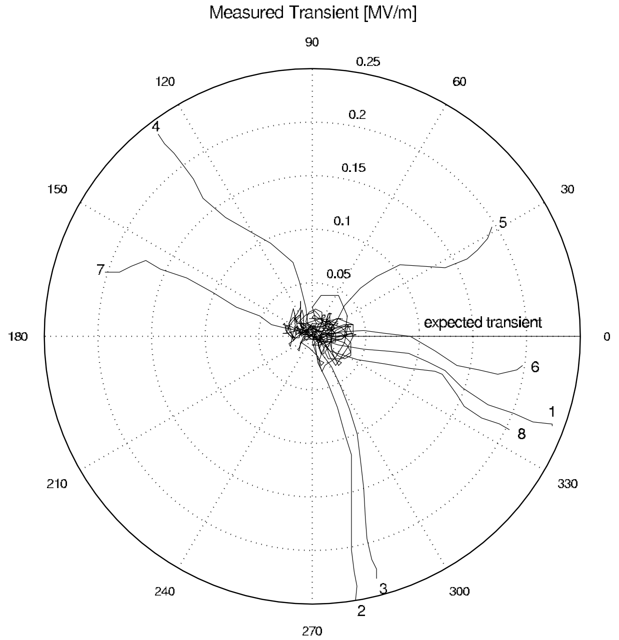

Figure 5: Measurement of beam induced transients (vectors) displayed as the difference of the cavity field with and without transient during the beam pulse. The phase of the transient defines the on-crest phase (zero) while the magnitude of the transient can be calculated from bunch charge and cavity shunt impedance. Normalized to the cavity field at the begin of the beam pulse, the transient is a measure for the phase of the beam relative to the accelerating field. From this plot one obtains the sensitivity of this method since the plot starts 50 µs before the beam pulse indicating the measurement noise.

The rf control system assists the operator through extensive diagnostic capabilities inherent to the digital design approach. During the initial start-up the individual cavity gradients and phases relative to the beam are calibrated using beam induced transients. Additional information provided are the phases of the incident waves which are adjusted to be equal in all cavities by means of three stub waveguide tuners. The calibration is verified by a spectrometer based measurement of the beam energy.

The requirements of $\sigma_A/A \le 2\cdot10^{-3}$ for amplitude stability and of $\sigma_\phi \le 0.5°$ phase stability can be achieved with a feedback gain of 70. The residual fluctuations are dominated by a repetitive component which can be further reduced by a factor of 10 with the adaptive feedforward thereby exceeding the design goals significantly. The high degree of field stability is mainly due to the low microphonic noise levels. A typical result of measured field stability without and with the adaptive feedforward is shown in Figure 6.

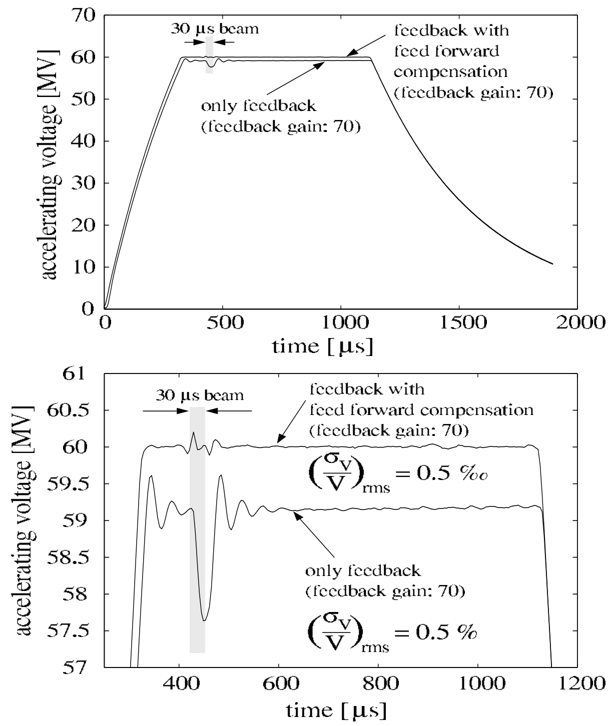

Figure 6: RF control performance with feedback only (gain=70) and additional feedforward applied. The adaptive feedforward improves the field stability by an order of magnitude since the repetitive errors are the dominant source of perturbations.

7 REFERENCES

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